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SHORT COMMUNICATION

JUMPING OF BELL HOUSES CAUSED BY NEAR-FIELD GROUND MOTION. CASE HISTORIES AND SHAKING TABLE EXPERIMENT

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SUMMARY

Earthquake-induced jumping of Bell Houses evidenced in epicentral areas of two earthquakes is discussed here. The earthquakes are the 1995 Hyogoken-nanbu, Japan earthquake and the 1909 Anegawa, Japan earthquake. Site-investigation was conducted to estimate vibration characteristics of the House and the ground. A series of shaking-table experiments, using models of a Bell House, demonstrated that the jumping followed by remarkable displacement can take place even by horizontal ground motion alone, when the strong motion is abruptly applied in the direction diagonal to the framework of the Bell House. The jumping process in the model experiment seems to be consistent with observations at real Bell Houses. © 1997 by John Wiley & Sons, Ltd. Earthquake eng. struct. dyn. 26: 657–665, 1997.

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KEY WORDS: near-field; earthquake-induced jumping; Bell House; shaking-table experiment; case histories

INTRODUCTION

Recent destructive earthquakes such as the 1994 Northridge, California and the 1995 Hogoken-nanbu, Japan earthquakes have highlighted urgent necessity to take account of near-field ground motion in seismic design of urban facilities. However, characteristics of the near-field strong motion are not well known to a satisfactory level of accuracy, mainly due to the limited number of the recordings. To supplement the scarcity of the recordings, back analyses of evidences are sometimes conducted using numerical or experimental methods. The authors[1] conducted a simulation of jumping displacement of boulders observed in the near-field of a Japanese earthquake, and confirmed that the jumping of objects could be an indicator of ground motion intensity.

This paper deals with the jumping of Bell Houses evidenced in epicentral areas of a recent and a past earthquakes in Japan. Referring to the case histories, the jumping is reproduced by shaking-table experiments using models of Bell Houses to find a key to the associated ground motion characteristics.

TRADITIONAL BELL HOUSES IN JAPAN

As schematically shown in Figure 1, a traditional Bell House, usually located in a precinct of a Japanese temple, is mainly made of wooden columns and beams, a tiled roof, and shoe-stones. The house has no walls

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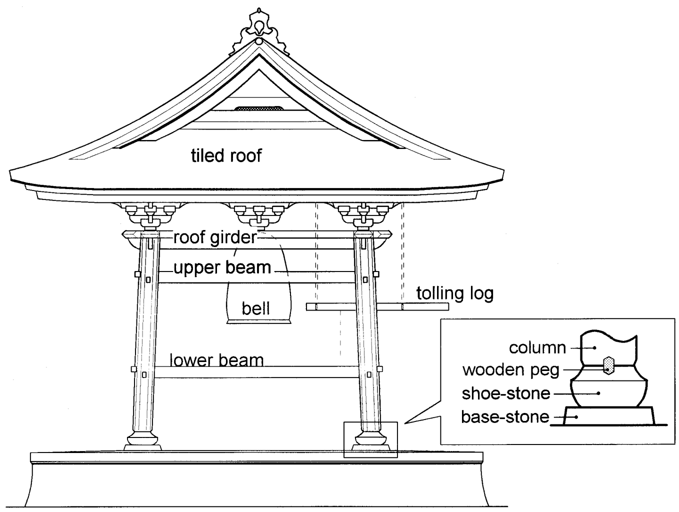


Figure 1. Schematic explanation of a Japanese Bell House

between the columns, but has a large bronze bell hanging under its ceiling. The bell is tolled at the outside wall by a log, suspended horizontally.

The Bell House is a typical top-heavy structure, because the tiled roof is much heavier than other elements. Four columns supporting the roof are connected with roof girders at the top, and also connected with slender upper- and lower-beams at the middle. At a beam-column joint, one end of a beam is simply plunged through a column, like a mortise joint, without using nails so that the joints are flexible rather than rigid.

To ensure stability of a Bell House, each column is slightly inclined outward from top to bottom by a half to twice its diameter. Between a column bottom and a shoe-stone, a wooden peg is usually inserted to keep them in contact, as shown in Figure 1. The round shoe-stones are mounted on square base-stones which are partially embedded in the ground.

A CASE IN THE 1995 HYOGOKEN-NANBU, JAPAN EARTHQUAKE

The 1995 Hyogoken-nanbu earthquake[2] ($M_J = 7{\cdot}2$) occurred on 17 January 1995. The focal mechanism of the earthquake was right-lateral strikes-slip with a slight dip-slip component. Surface rupture with an average horizontal displacement of 1–1·5 m appeared along the Nojima fault on Awaji Island, while no trace of surface faulting was discovered in and around Kobe City.

Because the percentage of housing collapse was more than 30 per cent, the highest seismic intensity 7 on the JMA scale was assigned to the areas shown by hatch in Figure 2. On Awaji Island, the intensity 7 was assigned to three hatched areas; Hokudan-cho, Ichinomiya cho and Tuna-cho, as shown in Figure 2.

In the near-field region on the Kobe side, many strong motion recordings of the main shock were recovered, indicating peak ground accelerations as high as 0·8g and 0·4g in the horizontal and vertical directions, respectively, with corresponding peak velocities of 1·5 and 0·6 m/s in each direction. Several of the peak horizontal velocities are also shown in Figure 2. The strong motion time histories in the near-field showed large pulses with period of around 1 s, and they were strongly polarized in the direction perpendicular to the fault line. Meanwhile no strong motion recording was recovered on Awaji Island.

At Saimyo-ji ("ji" means temple in Japanese) located in Ichinomiya-cho on Awaji Island, the jumping of a Bell House was evidenced. The site is located on delta ground surrounded by mountains. Predominant periods of the ground were estimated to be 0·3 and 1·0 s from microtremor measurement.

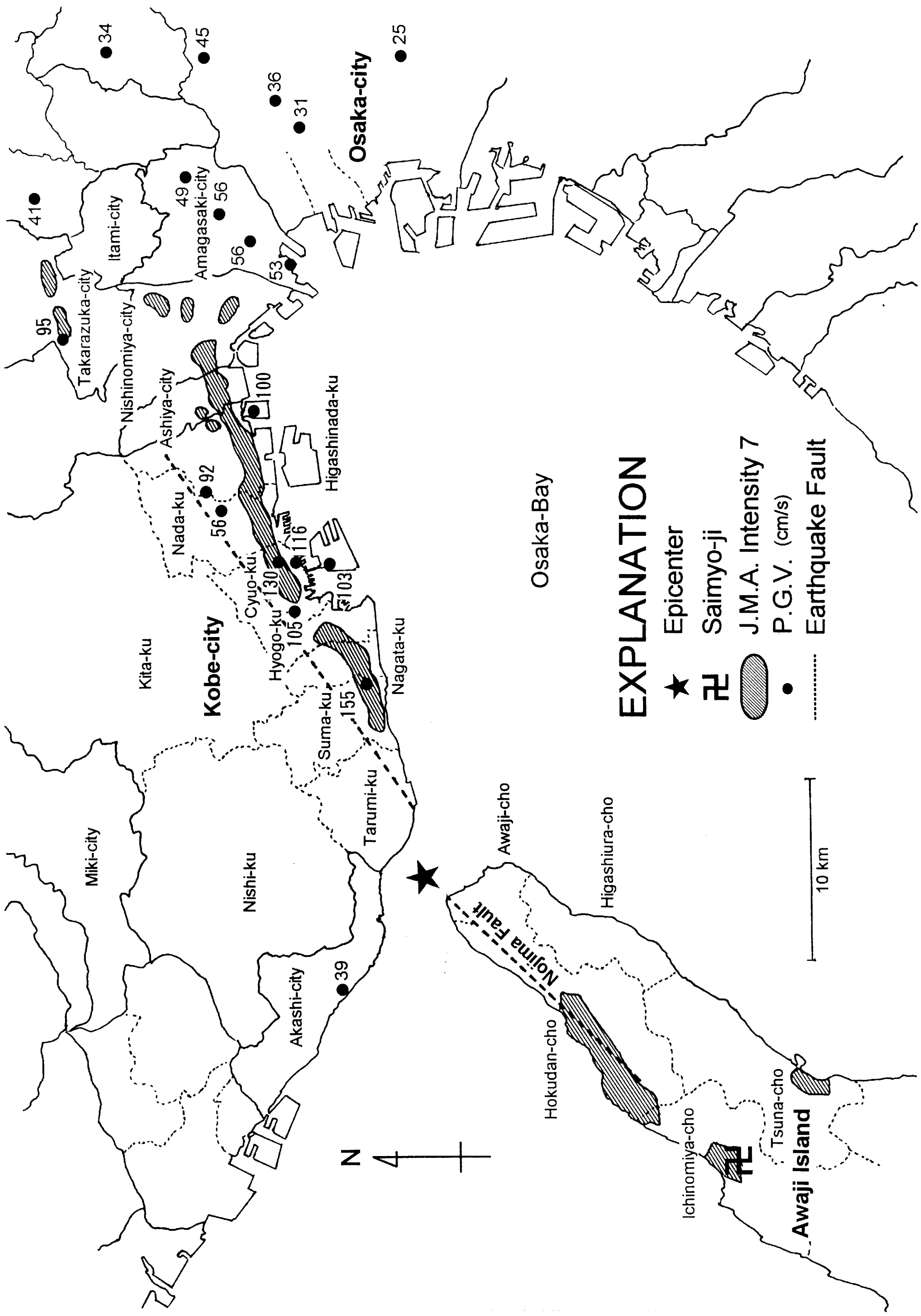


Figure 2. Map of Awaji Island and Kobe City, indicating areas of the seismic intensity 7 by hatch

Figure 3. Photo of the Bell House at Saimyo-ji after the 1995 Hyogo-ken Nanbu earthquake

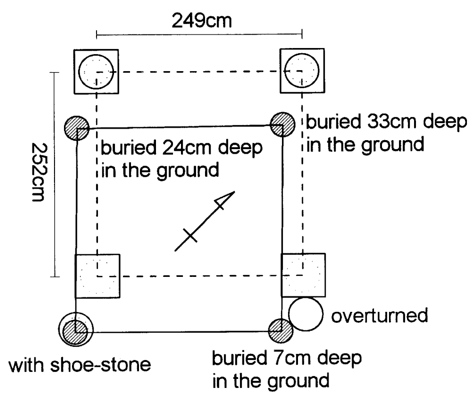


Figure 4. Displacement of the Bell House at Saimyo-ji

Figure 3 shows the Bell House at Saimyo-ji after the earthquake. The displaced House was inclined a little because one of the shoe-stones jumped with a column, and also because the floor slab of concrete was partly broken due to the landing impact of the House.

Figure 4 shows post-earthquake locations of shoe-stones and column-bottoms by open and hatched circles, respectively. In the figure, broken and solid lines, respectively, indicate original and displaced positions of the whole Bell House. The jumping was about 75 cm to the southeast, and the direction was almost perpendicular to an extension line of the Nojima fault.

CASES IN THE 1909 ANEGAWA, JAPAN EARTHQUAKE

An earthquake of M6·8 occurred in the eastern part of Shiga Prefecture, Japan on 14 August 1909. Figure 5 shows the epicentral area and damage distribution.[3] Severe damage was reported on a low land area between the Ibuki Mountains and Biwa Lake. The subsurface layer of the area mainly consists of soft clay, underlaid by sedimentary soils. Solid circles in Figure 5 indicate five temples where the earthquake-induced jumping of

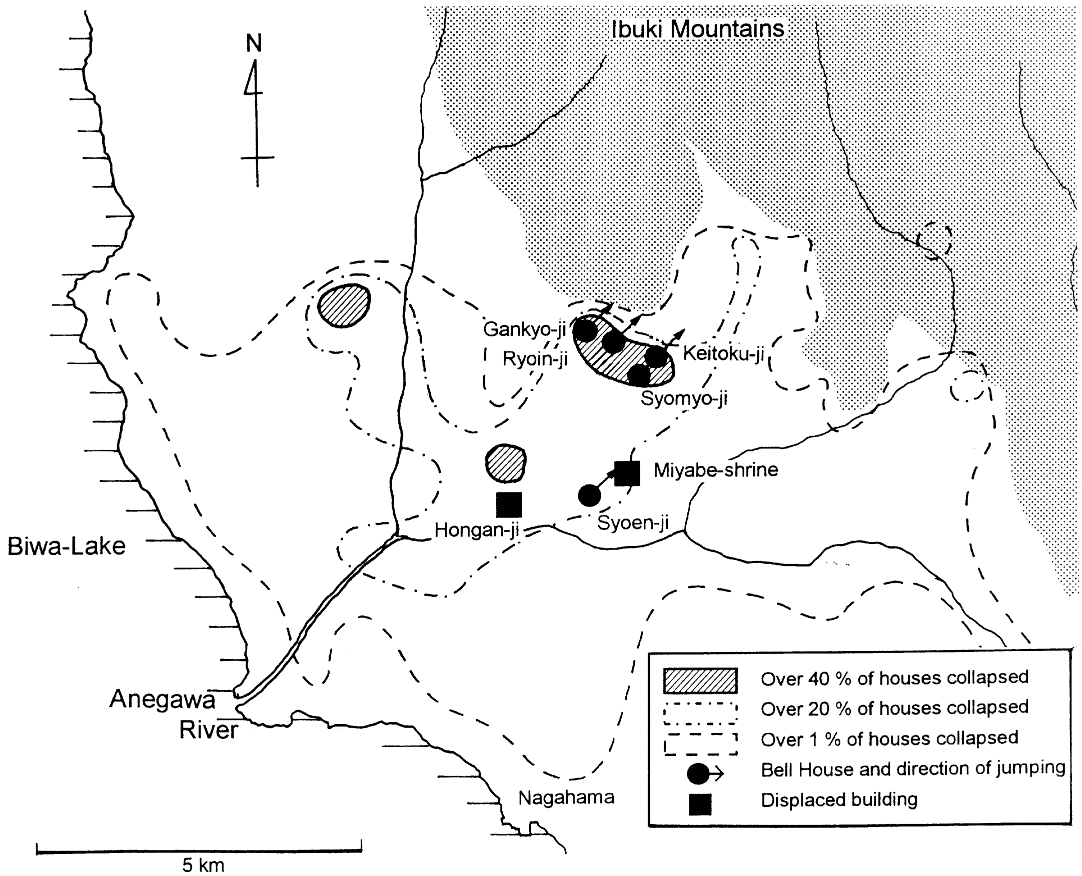


Figure 5. Damage distribution of the 1909 Anegawa earthquake

Bell Houses was evidenced. In addition, a $22m^2$ main building of Hongan-ji located to the south of the Bell Houses, as indicated by a solid square in Figure 5, was dislodged toward the S30°E direction by 22 cm at the front columns. At Miyabe-shrine denoted by another solid square in Figure 5, the main building was dislodged toward the northeast direction by 30 cm. As a whole, several objects including the five Bell Houses showed remarkable jumping displacement of 50 cm to 1 m toward the NE or NNE direction, suggesting a very strong ground motion in that direction.

Among the five Bell Houses that jumped during the earthquake, the Bell House at Gankyo-ji has been well preserved for about 350 years, although its roof has been retiled even after the 1909 earthquake. This Bell House which is 321 cm × 288 cm square, faces toward either the NS or EW direction on its four sides. During the earthquake, it displaced about 1 m toward the NE direction at a jump, as shown in Figure 6. The northeast column was displaced 107 cm toward N40°E with its shoe-stone, and the bottoms of other columns buried 3·5–7 cm deep in the ground.

Wooden structural elements of the House such as columns and beams are made of logs and square lumbers of keyaki trees (zelkova). The tiled roof is about 5 m high and 4 m wide. Total mass of the House is about 5000 kg, including the bronze bell of about 400 kg. To detect vibration characteristics, ambient vibration of the Bell House was measured with sensors placed on the roof girders and on the ground, with a result of the natural period of 0·5 s and the damping ratio of 5 per cent for the fundamental sway-mode. The periods of the hanging bell and of the ground were 1·8 and 0·9 s, respectively.

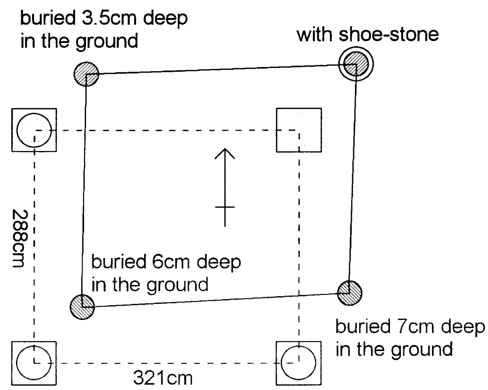


Figure 6. Displacement of the Bell House at Gankyo-ji[3]

SHAKING-TABLE EXPERIMENTS

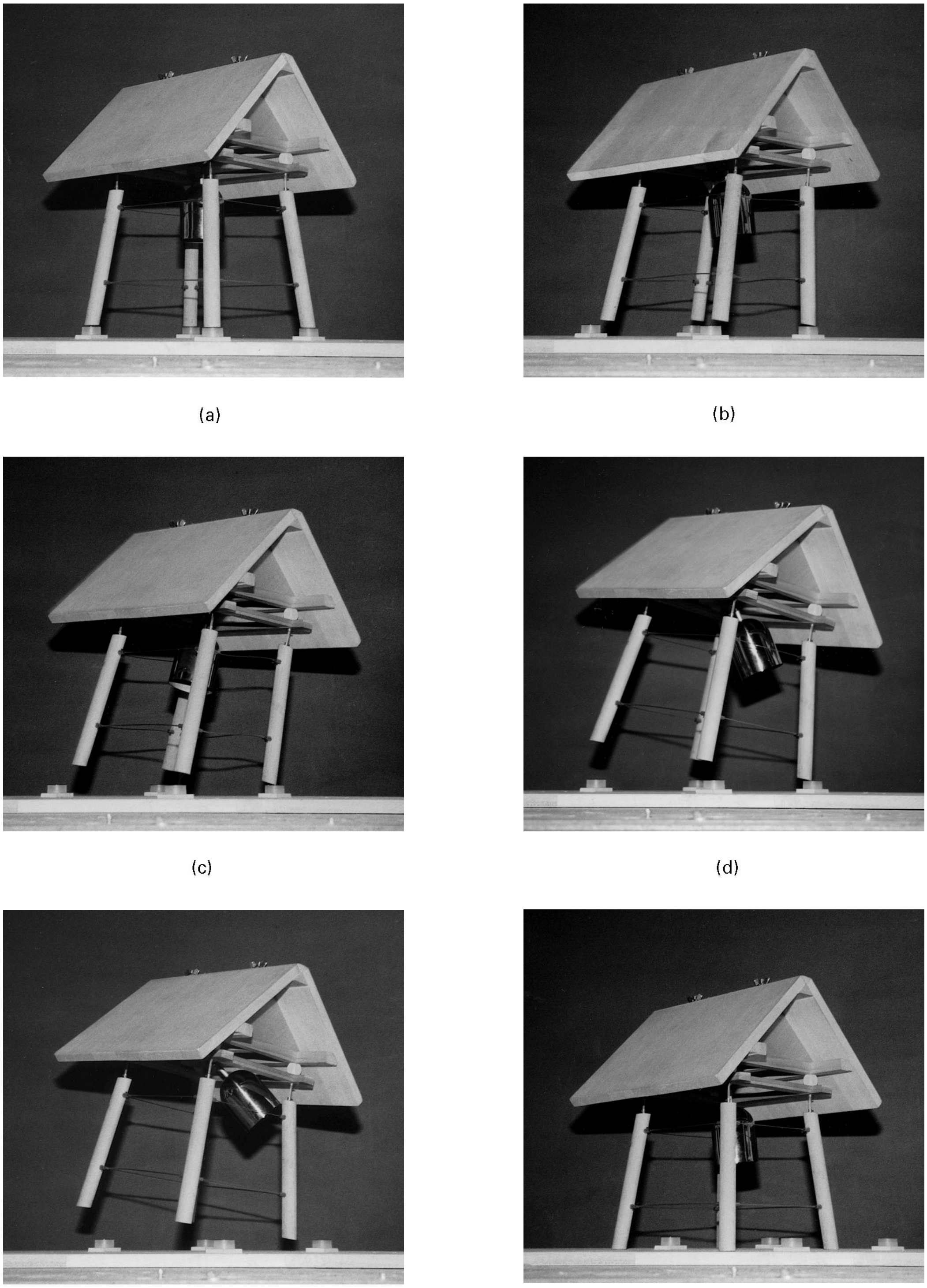
A series of experiments was conducted by using a small model rested on the shaking table which was movable in one horizontal direction only. The size of the model was set to 1/15 of the Bell House at Gankyo-ji, but the weight of the roof portion and the flexibility of the beams were varied by changing additional weight under the roof, as well as by selecting different materials for the beams. As a result, the vibration period of the model could be varied between 0·1 and 1·0 s. During the experiment, horizontal and vertical accelerations were measured simultaneously at the shaking table and at the top of the roof.

First, the model was shaken in a direction parallel to its frame. With a gradual increase in the table-motion acceleration, the model began back-and-forth rocking motion at a certain level of input acceleration. But even when the input acceleration exceeded lg, the model showed only the rocking motion without jumping.

After many trials and errors, the model was found to give rise to a remarkable jumping when it was suddenly shaken in its diagonal direction with an acceleration amplitude exceeding 0·4g at a period almost equal to its vibration period. It is of interest to note that the directions of observed displacements of Bell Houses shown in Figures 4 and 6 were also diagonal to their frames.

Photos in Figure 7 show several snap shots of the jumping. When the still standing model shown in (a) is suddenly subject to a sinusoidal table shaking, its roof leans forward a little and then turns back, while the hanging-bell lags behind the roof as shown in (b). As the roof increases the backward displacement, it leans on one column with other three columns uplifted as shown in (c). During the stages (b) and (c), a considerable flexure is seen at the beams connected with the supporting column that keeps in touch with the base. Thus, the distance between the supporting column and the farthest one is remarkably shortened at their bottoms. The distortion may be called a pantograph-like distortion. As shown in (d) and (e), the whole of the model jumps off the table with all the beams stretched again. Finally, the column-bottoms land on the table, and the model leaves large displacement as shown in (f).

Figure 8 shows acceleration observed in the experiment. Vertical lines denoted by 1, 2 and 3 indicate time instants when the three columns became uplifted, the whole model started to jump and it landed on the table in that order. The table motion acceleration shown at the top exceeded 600 cm/s^2 at its second peak. As shown at the second from the top and at the bottom of Figure 8, respectively, both horizontal and vertical accelerations of the roof exceeded 1g, which demonstrates that the large vertical response can be produced even by the horizontal table motion alone. The third time history in Figure 8 indicates response acceleration of the roof relative to the table. According to velocity time histories obtained by integrating the accelerations, the peak velocity of the table motion was 36 cm/s, while that of the roof relative to the table was amplified to



(a) (b) (c) (d) (e) (f)

Figure 7. Snap shots of jumping of model Bell House

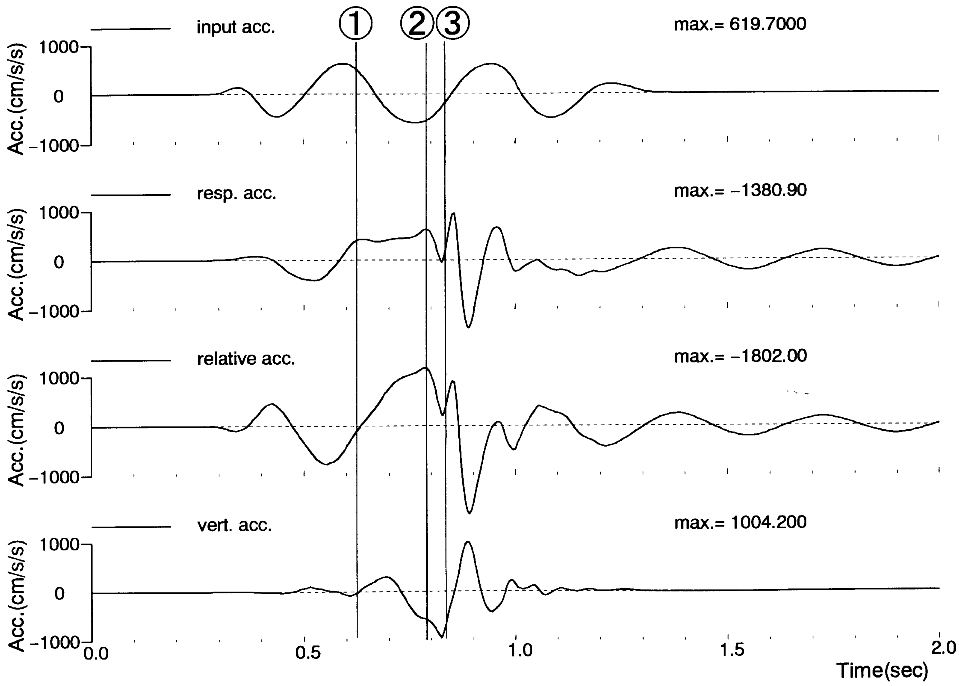


Figure 8. Accelerations of shaking table and model Bell House

60 cm/s. The frequency of the table motion in this case was about 3 Hz, which was coincident with the vibration frequency of the model.

DISCUSSION AND CONCLUDING REMARKS

As shown in Figure 2, the near-field strong motion records of the 1995 Hyogoken-nanbu earthquake indicated 1–1·5 m/s in peak velocities. If a Bell House is subject to such intense ground motion at its resonant period, its response velocity will reach 3–4 m/s, amplified 2 to 3 times as large as the input motion. Then, it seems reasonable to think that the House can show the jumping displacement of 0·5–1 m, as evidenced in the actual cases mentioned earlier.

To infer more detailed characteristics of the ground motion associated with the jumping, further studies should be devoted to sophisticated earthquake response analysis of the Bell Houses, For such studies, the following findings from the present study will provide a key to the point:

1. A Bell House is likely to produce large displacement at a jump, when it is suddenly shaken in its diagonal direction. Otherwise it tends to produce rocking motion only, even when very strong ground motion is input.
2. When the jumping is produced, a Bell House is distorted like a horizontal pantograph with its three columns uplifted. Due to this distortion, the Bell House is upthrown at a low angle.
3. Accordingly, the jumping of a Bell House can be produced even by the horizontal ground motion alone.
4. For the jumping, the ground motion needs to have large intensity at a period almost equal to the vibration period of the Bell House.

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